

A toy model for X-ray spectral variability of active galactic nuclei

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ABSTRACT

The long term X-ray spectral variability of ten active galactic nuclei (AGN) shows a positive spectral index-flux correlation for each object (Sobolewska & Papadakis 2009). An inner ADAF may connect to a thin disc/corona at a certain transition radius, which are responsible for hard X-ray emission in AGN. The ADAF is hot and its X-ray spectrum is hard, while the corona above the disc is relatively cold and its X-ray spectrum is therefore soft. The radiation efficiency of the ADAF is usually much lower than that of the thin disc. The increase of the transition radius may lead to decreases of the spectral index (i.e., a hard spectrum) and the X-ray luminosity even if the accretion rate is fixed, and vice versa. We propose that such X-ray variability is caused by the change of the transition radius. Our model calculations can reproduce the observed index-flux correlations, if the transition radius fluctuates around an equilibrium position, and the radiation efficiency of ADAFs is ~ 5 per cent of that for a thin disc. The average spectral index-Eddington ratio correlation in the AGN sample can also be reproduced by our model calculations, if the equilibrium transition radius increases with decreasing mass accretion rate.

Key words: accretion, accretion discs—black hole physics—quasars: general.

1 INTRODUCTION

The X-ray emission of luminous active galactic nuclei (AGN) is believed from the inner region of the accretion disc surrounding a massive black hole (e.g., Haardt, Maraschi, & Ghisellini 1994). In the accretion disc model, the observed optical/UV continuum spectra are supposed to originate from the accretion disc (Shields 1978; Malkan & Sargent 1982), while the hard X-ray emission is from the corona above the disc (Galeev, Rosner, & Vaiana 1979; Haardt & Maraschi 1991, 1993). The gravitational energy of the gas is predominantly released in the accretion disc, and a fraction of it is transported into the corona, and therefore the electrons in the corona are heated up to high temperatures $\sim 10^9$ K (Del Santo et al. 2008; Di Matteo, Celotti, & Fabian 1999; Merloni & Fabian 2001, 2002; Liu, Mineshige, & Ohsuga 2003; Cao 2009). The corona is optically thin, and only a small fraction of the soft photons in optical/UV bands are inverse Compton scattered to hard X-ray bands by the hot electrons in the corona. This is the most favorite scenario for the power law X-ray continuum ubiquitously observed in luminous AGN (Galeev, Rosner, & Vaiana 1979; Haardt & Maraschi 1991, 1993).

The observational features of low luminosity AGN (with Eddington ratio lower than ~ 0.01) are different from their luminous counterparts, most of which lack of optical/UV bumps in their continuum spectra and broad emission lines (see Ho 2008, for a re-

view). The X-ray spectral indices of low luminosity AGN are systematically lower than luminous AGN (e.g., Lu & Yu 1999). The statistic study on the optical/UV/X-ray emission shows evidence that the central engines in low luminosity AGN are different from those in luminous counterparts (Xu 2011). It was suggested that advection dominated accretion flows (ADAF) are present in low luminosity AGN (see Narayan 2002, for a review), which are different from the standard thin accretion discs in luminous AGN. The radial velocity of ADAFs is high, typically several tens per cent of the Keplerian velocity, and their gas density is low, which leads to low radiation efficiency (Narayan & Yi 1995). The typical electron temperature of the ADAFs can be about one order of magnitude higher than the temperature of the electrons in the corona above the disc (e.g., Xu & Cao 2010), and the X-ray spectra of ADAFs are naturally harder than those of the corona in luminous AGN.

The X-ray emission provides useful clues on the physics of central engines in AGN. Both the hard X-ray spectral index and the fraction of X-ray to bolometric luminosity L_X/L_{bol} are found to be correlated with the Eddington ratio for a luminous AGN sample (Wang, Watarai, & Mineshige 2004). These two correlations can be explained by the accretion disc corona model (Cao 2009). Unlike luminous AGN, Gu & Cao (2009) found that the X-ray spectral index is anti-correlated with the Eddington ratio for a low luminosity AGN sample, which is confirmed by some other works (Younes et al. 2011, 2012; Emmanoulopoulos et al.

2012). Similar features are also observed in some X-ray binaries (e.g., Zdziarski, Lubinski, & Smith 1999; Zdziarski et al. 2004; Wu & Gu 2008; Cao, Wu, & Dong 2014; Dong, Wu, & Cao 2014). The optical depth of Compton scattering in ADAF increases with the dimensionless mass accretion rate \dot{m} ($\dot{m} = \dot{M}/\dot{M}_{\text{Edd}}$), and therefore the spectral index decreases with \dot{m} . The anti-correlation between spectral index and Eddington ratio can be qualitatively explained with the ADAF model (Gu & Cao 2009).

It is known that many AGN exhibit variability in different time scales. The long term X-ray spectral variability of ten active galactic nuclei (AGN) has been studied with the data of *Rossi X-ray Timing Explorer (RXTE)* observations over ~ 10 years, in which a similar spectral index-flux correlation is found for all objects (except for NGC 5548) over a large range of flux (Sobolewska & Papadakis 2009). Such X-ray “softer when brighter” behavior can not be interpreted with X-ray absorption by a single medium whose ionization level follows the continuum flux variations. The model of a constant reflection component plus a power law continuum with constant spectral slope and variable flux is also disfavored, indicating the intrinsic continuum is variable both in flux and in shape (Sobolewska & Papadakis 2009).

The accretion mode transition is mainly triggered by the dimensionless mass accretion rate \dot{m} , which is sensitive to the value of the viscosity parameter α (see Narayan 2002; Yuan & Narayan 2014, for reviews). Although the detailed physics of accretion mode transition is still unclear, it may be regulated by the processes in the accretion disc corona systems, i.e., the evaporation of the disc and/or condensation of the hot gas in the corona (Meyer-Hofmeister & Meyer 1999; Liu et al. 1999). An alternative scenario for accretion mode transition being triggered by the thermal instability was suggested by Abramowicz et al. (1995). It was indeed found that a small fraction of low luminosity AGN have optical bumps in their continuum spectra with hard X-ray spectra, of which the multi-band spectral energy distributions can be well reproduced by the ADAF+standard thin accretion disc model (e.g., Quataert et al. 1999; Yuan & Narayan 2004; Xu & Cao 2009). This provides evidence for accretion mode transition in AGN. Zdziarski, Lubinski, & Smith (1999) proposed that a hot plasma (probably an ADAF) surrounded by a cold disc can reproduce the observed correlation between the X-ray spectral index and the reflection parameter $R = \Omega/2\pi$ (Ω is the solid angle subtended by the reflector) in Seyfert AGNs and the hard state of X-ray binaries. In this scenario, the power of soft photons from the cold disc increases with decreasing of the inner radius of the cold disc, which leads to thermal Comptonization amplification factor A decreasing and softer X-ray spectra.

In this work, we suggest that the variation of the transition radius between the ADAF and thin disc/corona is responsible for the observed X-ray variability in AGNs. In Sect. 2, we describe the model calculations. The results and discussion are in Sects. 3 and 4.

2 MODEL

We consider that the black hole is surrounded by an ADAF accreting at a critical rate \dot{m}_{crit} , which connects to a thin accretion disc with corona at a transition radius R_{tr} . The observed X-ray emission originates from the inner ADAF and the corona above the disc in the outer region. It was found that the X-ray spectral index is correlated with the Eddington ratio for bright AGNs. The photon spectral index $\Gamma \sim 2 - 2.5$ for the sources with Eddington ra-

tio $\gtrsim 0.1$, while it decreases to ~ 1 if Eddington ratio ~ 0.01 (Wang, Watarai, & Mineshige 2004; Shemmer et al. 2006, 2008). For low luminosity AGNs, the X-ray spectra are systematically harder than those of bright AGNs. Their X-ray spectral index is anti-correlated to the Eddington ratio. The photon spectral index $\Gamma \sim 1$ for the low luminosity AGNs at high Eddington ratio end (Younes et al. 2011). The observed correlations can be reproduced by the accretion corona/ADAF models (Cao 2009; Qiao & Liu 2013). In this work, we do not intend to get into the complexity of the detailed physics of these models, and we adopt the X-ray spectral indices of the corona and ADAF as input model parameters. The location of the transition radius between the inner ADAF and the thin disc corona is still unclear, which is believed to be related to values of the disc parameters, such as, the viscosity parameter α , mass accretion rate \dot{m} , and even the magnetic field strength in the disc (e.g., Meyer-Hofmeister & Meyer 1999; Liu et al. 1999; Kawaguchi, Shimura, & Mineshige 2001; Taam et al. 2012). It is known that the radiation efficiency of ADAFs is significantly lower than that of thin accretion discs, which means that the radiation power from an ADAF+thin disc/corona system varies with transition radius even if the mass accretion rate remains constant. We assume that the observed X-ray variability in AGNs is mainly caused by the transition radius fluctuation around the equilibrium position.

We use a correction factor f_{cor} to relate the bolometric luminosity L_{bol} to the X-ray luminosity $L_{X,2-10\text{keV}}$ in 2–10 keV,

$$L_{\text{bol}} = f_{\text{cor}} L_{X,2-10\text{keV}}. \quad (1)$$

A typical value of $f_{\text{cor}}^{\text{b}} = 30$ is adopted for bright AGN (Runnoe, Brotherton, & Shang 2012). The relative contribution of X-ray photons to the spectral energy distribution (SED) of low luminosity AGN is higher than their high luminosity counterparts. Ho (1999) found that $L_{\text{bol}}/L_X = 3 - 17$ for a small sample of low luminosity AGN with well measured SED. The SED of low-luminosity AGN can be well fitted with the ADAF model. In this work, we adopt $f_{\text{cor}}^{\text{f}} = 10$ for the radiation from ADAFs.

For luminous AGN, the bolometric luminosity of the accretion disc with corona is

$$L_{\text{bol}} = \eta_{\text{rad}} \dot{M} c^2, \quad (2)$$

where \dot{M} is the mass accretion rate, and η_{rad} is the radiation efficiency. For radiatively efficient accretion discs, the radiation efficiency η_{rad} is in the range of $\sim 0.05 - 0.3$, which is a function of the black hole spin parameter a . For simplicity, we limit our calculations in the Newtonian frame. The radiation efficiency is

$$\eta_{\text{rad}} = \frac{1}{2r_{\text{in}}}, \quad (3)$$

where $r_{\text{in}} = R_{\text{in}}/R_g$ ($R_g = GM_{\text{bh}}/c^2$) is the inner radius of a radiatively efficient accretion disc.

In the case of the accretion disc corona truncated at radius R_{tr} , its X-ray luminosity is

$$L_{X,2-10\text{keV}}^{\text{cor}} \simeq \frac{\eta_{\text{rad}} \dot{M} c^2}{f_{\text{cor}}^{\text{b}}} \left(\frac{R_{\text{in}}}{R_{\text{tr}}} \right) = \frac{\dot{M} c^2}{2r_{\text{tr}} f_{\text{cor}}^{\text{b}}}, \quad (4)$$

where equation (3) is used, and $r_{\text{tr}} = R_{\text{tr}}/R_g$.

The radiation efficiency of the inner ADAF within $R \leq R_{\text{tr}}$ is much lower than that of a standard thin accretion disc. The precise value of the efficiency is still quite uncertain, which is sensitive to the mass accretion rate \dot{m} and the viscosity parameter α (e.g., Xu & Cao 2010). Assuming $\eta_{\text{rad}}^{\text{ADAF}} = f_{\eta}^{\text{ADAF}} \eta_{\text{rad}}$ ($f_{\eta}^{\text{ADAF}} < 1$), we have

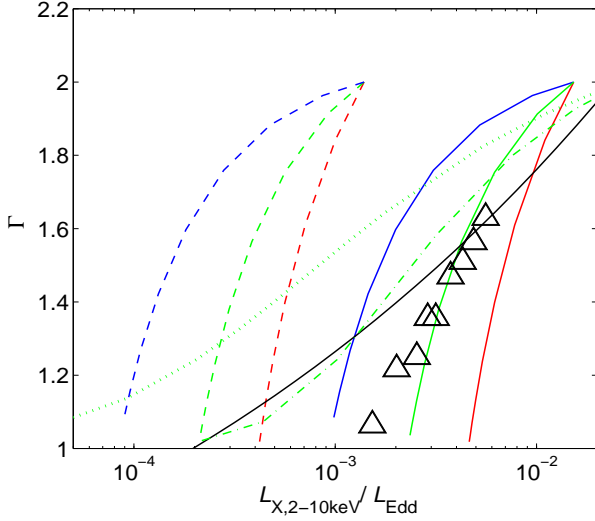


Figure 1. The relations of the photon spectral index with the Eddington ratio for different values of parameters. The solid coloured lines represent the cases with $\dot{m} = 0.55$, while the dashed lines are for $\dot{m} = 0.05$. The coloured lines indicate the results with different values of radiation efficiency for ADAFs, $f_{\eta}^{\text{ADAF}} = 0.1$ (red), 0.05 (green), and 0.02 (blue). The triangles are the binned spectral index-flux data of NGC 3516, which are shifted to right by ~ 0.5 dex compared with those in Sobolewska & Papadakis (2009) due to the updated black hole mass measurement. The black solid line indicates the best-fitting correlation between average spectral index and mass accretion rate derived from the AGN sample with the updated black hole mass data (see the text in Sect. 3). The results with varying mass accretion rate model calculations are plotted as the dotted line ($p = 1$, see equation 7) and the dash-dotted line ($p = 2$).

$$L_{X,2-10\text{keV}}^{\text{ADAF}} \simeq \frac{f_{\eta}^{\text{ADAF}} \eta_{\text{rad}} \dot{M} c^2}{f_{\text{cor}}^f} \left(1 - \frac{R_{\text{in}}}{R_{\text{tr}}}\right) = \frac{f_{\eta}^{\text{ADAF}} \dot{M} c^2}{2r_{\text{in}} f_{\text{cor}}^f} \left(1 - \frac{r_{\text{in}}}{r_{\text{tr}}}\right), \quad (5)$$

for an ADAF truncated at r_{tr} . For the accretion flows surrounding non-rotating black holes, $R_{\text{in}} = 6R_{\text{g}}$. The X-ray luminosity of the ADAF+thin disc corona system in 2–10 keV is

$$L_{X,2-10\text{keV}} = L_{X,2-10\text{keV}}^{\text{ADAF}} + L_{X,2-10\text{keV}}^{\text{cor}}. \quad (6)$$

In this work, we adopt the critical mass accretion rate \dot{m}_{crit} as an input parameter in the model calculations. The hard X-ray luminosity and spectral shape of ADAF+thin disc corona system changing with the transition radius r_{tr} can be calculated with equations (4)–(6), provided the spectral indices of the X-ray spectra from the ADAF and the outer thin disc corona are known.

3 RESULTS

Using equations (4)–(6), we can calculate the relation between the X-ray luminosity and spectral shape by changing the value of transition radius r_{tr} , if the values of the mass accretion rate \dot{m} , the inner radius r_{in} of the ADAF, and f_{η}^{ADAF} are specified. In the calculations, we assume that the photon spectral index of the hard X-ray emission in 2–10 keV from the corona of the disc, $\Gamma_{\text{cor}} = 2$, and $\Gamma_{\text{ADAF}} = 1$ for the X-ray spectrum from the inner ADAF (Younes et al. 2012). The inner radius of the accretion disc $r_{\text{tr}} = 6$ is adopted in our calculations. We plot the results with different

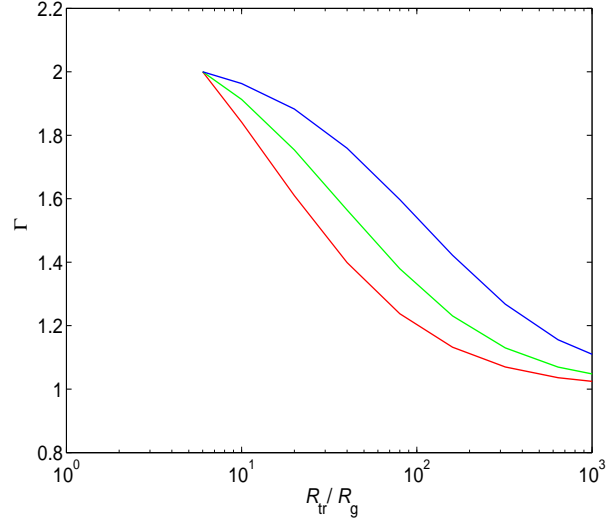


Figure 2. The photon spectral indices as functions of transition radius r_{tr} . The coloured lines indicate the results with different values of radiation efficiency for ADAFs, $f_{\eta}^{\text{ADAF}} = 0.1$ (red), 0.05 (green), and 0.02 (blue).

values of the parameters in Fig. 1, and the spectral indices Γ as functions of the transition radius r_{tr} are plotted in Fig. 2.

It was suggested that the stationary transition radius may vary with the mass accretion rate as

$$r_{\text{tr}} = r_{\text{tr},0} \left(\frac{\dot{m}}{\dot{m}_0} \right)^{-p}, \quad (7)$$

where $p \sim 0.5 - 2$ for different accretion mode transition mechanisms (see Czerny, Rózańska, & Kuraszkiewicz 2004, for the detailed discussion). In Fig. 1, we plot the results of the varying mass accretion rate model with $r_{\text{tr},0} = r_{\text{in}}$ and $\dot{m}_0 = 1$ adopted. It is found that the result calculated with $p = 2$ agrees quite well with the global correlation between average spectral index and mass accretion rate for the AGN sample.

In our model, we assume that the transition radius between the ADAF and the thin disc corona varies with time. We have to estimate the timescale of variability caused by the variation of R_{tr} . The timescale of the transition radius moving toward the black hole is comparable with the viscous timescale of the thin disc at R_{tr} , which can be estimated with

$$\tau_{\text{vis}} \sim \frac{R_{\text{tr}}}{v_R} = \frac{R_{\text{tr}}^2}{\alpha c_s H} = 1.56 \times 10^{-7} r_{\text{tr}}^{3/2} \alpha^{-1} \left(\frac{H}{R} \right)^{-2} \left(\frac{M_{\text{bh}}}{10^6 M_{\odot}} \right) \text{ years}, \quad (8)$$

where the viscosity parameter $\alpha < 1$, and H is the disc thickness (Shakura & Sunyaev 1973). We note that the black hole masses of four sources in Sobolewska & Papadakis (2009) are around $10^6 M_{\odot}$, one is about $10^8 M_{\odot}$, and the remainders are $\sim 10^7 M_{\odot}$. We find that the black hole masses of some sources in their work were overestimated. The updated black hole mass measurements with broad line profiles for some sources show that (see Sobolewska & Papadakis 2009, for comparison), $1.06 \times 10^8 M_{\odot}$ (Fairall), $7.13 \times 10^5 M_{\odot}$ (NGC 4051), $3.19 \times 10^6 M_{\odot}$ (NGC 3227), $2.78 \times 10^7 M_{\odot}$ (NGC 5548), $1.24 \times 10^7 M_{\odot}$ (NGC 3783), and $1.32 \times 10^7 M_{\odot}$ (NGC 3516) (Graham et al. 2011); $7.0 \times 10^6 M_{\odot}$ (NGC 5506) and $4.5 \times 10^6 M_{\odot}$ (MCG-6-30-15) (McHardy 2013). For typical values of the parameters, for example, $r_{\text{tr}} = 100$, $\alpha = 1$, $H/R = 0.05$ (corresponding to $\dot{m} = 0.5$ at $r_{\text{tr}} = 100$)

(e.g., see Loska, Czerny, & Szczerba 2004), and $M_{\text{bh}} = 10^7 M_{\odot}$, the viscous timescale $\tau_{\text{vis}} \sim 0.6$ year.

The cold disc is irradiated by the emission from the hot corona, and the evaporation of the gas in the cold disc is assumed to be balanced by the condensation of the gas in the corona in steady cases. The disc corona will transit to an ADAF when the evaporation dominates over the condensation. Thus, the typical timescale of the transition from the disc corona to an ADAF is comparable with the evaporation timescale. At the transition radius R_{tr} , all the gas in the cold disc is evaporated into the hot corona, and we have

$$\pi R_{\text{tr}}^2 \dot{M}_{\text{evap}}(R_{\text{tr}}) \sim \dot{M} = -2\pi R_{\text{tr}} \Sigma(R_{\text{tr}}) v_R, \quad (9)$$

where \dot{M}_{evap} is loss rate of the gas evaporated in unit surface area of the disc, and Σ is the surface density of the disc (Mineshige et al. 1998). The evaporation timescale can be estimated as

$$\tau_{\text{evap}} \sim \frac{\Sigma}{\dot{M}_{\text{evap}}} = -\frac{R_{\text{tr}}}{2v_R}. \quad (10)$$

Comparing with equation (8), we find that the viscous timescale of the disc is twice of the evaporation timescale. Considering the estimates of the timescales being at order of magnitude, a factor of two does not mean much. We simply adopt τ_{vis} as the typical timescale of the variability caused by the variation of the transition radius R_{tr} .

4 DISCUSSION

After taking account of a constant reflection component in the X-ray spectra¹, Sobolewska & Papadakis (2009) suggested the intrinsic X-ray photon index in individual AGNs varies as $\Gamma_{\text{intrinsic}} \sim F_{2-10\text{keV}}^{0.08}$, consistent with the average spectral index–accretion rate relation in their AGN sample. However, the assumption that the reflection component, which is believed from the accretion disc and the torus, does not respond to central continuum variations over ~ 10 years is questionable. The measured infrared lags in nearby Seyfert galaxies are in order of ~ 10 days to one year (Suganuma et al. 2006), indicating the reflection component from the torus should respond to central X-ray continuum variation within the observed timescale of Sobolewska & Papadakis (2009). The response of the disc reflection to the central continuum is more complicated than a constant component (Iwasawa et al. 1996; Wang et al. 1999, 2001; Shu et al. 2010; Fabian et al. 2002). Therefore, the intrinsic X-ray variation in individual AGNs should follow a slope steeper than $\Gamma_{\text{intrinsic}} \sim F_{2-10\text{keV}}^{0.08}$, and in this work, assuming the reflection component responds well to central X-ray emission, we compare the binned spectral index–flux data with our model (see the data points in Fig. 8 of Sobolewska & Papadakis 2009).

The emission from the corona decreases rapidly with increasing transition radius, and therefore the observed emission is predominantly from the inner ADAF truncated at a large radius r_{tr} , of which the spectrum is harder than that of the corona. Thus, we find that the spectral index decreases with flux even if the mass accretion rate is fixed (see Fig. 1). As a similar spectral index–flux correlation is present for most of the sources in the sample (Sobolewska & Papadakis 2009), we take the data of NGC 3516 as an example for comparison with our model. We find that the model calculation with a relative low $f_{\eta}^{\text{ADAF}} = 0.05$

can roughly reproduce the observed spectral index–flux data (the green line in Fig. 1). This is qualitatively consistent with the prediction of the theoretical works that the radiation efficiency of ADAFs is significantly lower than the standard thin accretion discs (see Narayan, Mahadevan, & Quataert 1998, for detailed discussion). The range of the observed variability of Γ can be reproduced when the transition radius r_{tr} fluctuates between r_{in} and several hundreds, if $f_{\eta}^{\text{ADAF}} \gtrsim 0.05$ (see Fig. 2). This is independent of the mass accretion rate \dot{m} . It is found that the timescale of the X-ray variability caused by the transition radius changing is at the order of one year for a typical AGN as NGC 3516 (see the discussion in Sect. 3), which can be as short as tens of days if $M_{\text{bh}} \sim 10^6 M_{\odot}$. This is roughly consistent with the observed light curves of these sources given in Sobolewska & Papadakis (2009). We find that $L_{X,2-10\text{keV}}/L_{\text{Edd}} = 3.8 \times 10^{-3}$ for NGC 3516, which is the minimal one in the sample with updated black hole mass data. This implies that the viscous timescales of other sources with similar or smaller black holes should be shorter than that of NGC 3516. For the sources with softer X-ray spectra, i.e., larger- Γ , most of the X-ray emission is from the corona, and the transition radius r_{tr} should be smaller, which corresponds a shorter viscous timescale. We find that $\dot{m} \gtrsim 0.5$ is required to reproduce the observations, which is slightly higher than that expected by the ADAF model even if $\alpha = 1$ (e.g., $\dot{m} \lesssim \dot{m}_{\text{crit}} \sim 0.3\alpha^2$ for an ADAF, see Narayan, Mahadevan, & Quataert 1998, for detailed discussion). The radial velocity of a thin accretion disc with magnetic outflows can be much higher than that of a normal viscously driven disc, if the angular momentum of the disc is removed predominantly by the outflows (Cao & Spruit 2013). This mechanism may work in the ADAF with magnetic outflows, and therefore its density would be lower than that predicted by the conventional ADAF model for a given mass accretion rate, which may lead to a higher critical accretion rate for accretion mode transition. Our present calculations are carried out with $r_{\text{in}} = 6$ for non-rotating black holes. The radiation efficiency of an accretion disc surrounding a spinning black holes is higher than the non-rotating black hole case. A higher radiation efficiency for a spinning black hole can be mimicked by tuning the value of r_{in} . We find that the results are similar to those reported in Figs. 1 and 2 even if a smaller r_{in} is adopted.

When the transition radius decreases, more gravitational power is released in the corona, and therefore the X-ray emission from the corona increases, while the emission from the inner ADAF decreases. The total X-ray emission increases with decreasing transition radius, because the radiation efficiency of the outer disc/corona is higher than that of the inner ADAF. The fraction of the X-ray emission from the corona to the ADAF increases with decreasing radius, which leads to the observed X-ray spectral index increasing with luminosity, as the X-ray emission from the corona is softer than that of the ADAF. The emission from the thin disc, mostly in optical/UV wavebands, is also expected to increase with X-ray emission. This is consistent with observations that reveal generally simultaneous long term optical/UV and X-ray variations in AGNs (e.g. Gaskell 2006). In this work, the X-ray spectral indices of the ADAF and corona are taken as input model parameters, whereas the spectral index of ADAF may decrease with increasing transition radius due to the interception of the soft photons from the outer disc by the ADAF (Zdziarski, Lubiński, & Smith 1999). If this effect is included, less fluctuation in transition radius is required to explain the observed X-ray variability.

The timescale of the variability caused by the transition radius is proportional to the black hole mass (see equation 8). This

¹ the amplitude of the constant reflection component was chosen to have $R = 1$ relative to the time-averaged continuum.

implies that only the sources with small black holes ($\lesssim 10^7 M_\odot$) will exhibit violent variability in the timescale of $\lesssim 1$ year. For those sources containing massive black holes ($\sim 10^{8-9} M_\odot$), the timescale of such variability can be as long as tens or hundreds of years, which may be impractical as monitoring objects.

The black holes are fed by the circumnuclear gas, and the accretion rate is predominantly regulated by the properties of the gas at the outer radius of the disc. The timescale of accretion rate changes is much longer than the X-ray variability timescale. So, the average X-ray flux may correspond to the composite emission from the ADAF and the corona connected at the equilibrium transition radius, which may vary with the mass accretion rate as expected by different physical mechanisms for accretion mode transition. The best-fitting average spectral index-mass accretion rate correlation for the AGN sample is roughly consistent with our calculations with $p = 2$ (see equation 7), which seems to support the thermal instability triggering accretion mode transition (Abramowicz et al. 1995). However, it should be cautious on this issue, because the correlation is derived with a sample of only ten sources. Further observation on a large sample of AGN may help understand the physics of the accretion mode transition.

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REFERENCES

- Abramowicz M. A., Chen X., Kato S., Lasota J.-P., Regev O., 1995, *ApJ*, 438, L37
- Cao X., 2009, *MNRAS*, 394, 207
- Cao X., Spruit H. C., 2013, *ApJ*, 765, 149
- Cao X.-F., Wu Q., Dong A.-J., 2014, *arXiv*, arXiv:1404.5316
- Czerny B., Rózańska A., Kuraszewicz J., 2004, *A&A*, 428, 39
- Del Santo M., Malzac J., Jourdain E., Belloni T., Ubertini P., 2008, *MNRAS*, 390, 227
- Di Matteo T., Celotti A., Fabian A. C., 1999, *MNRAS*, 304, 809
- Dong A.-J., Wu Q., Cao X.-F., 2014, *arXiv*, arXiv:1404.5317
- Emmanoulopoulos D., Papadakis I. E., McHardy I. M., Arévalo P., Calvelo D. E., Uttley P., 2012, *MNRAS*, 424, 1327
- Fabian, A. C., Vaughan, S., Nandra, K., Iwasawa, K., Ballantyne, D. R., Lee, J. C., De Rosa, A., Turner, A., & Young, A. J. 2002, *MNRAS*, 335, L1
- Galeev A. A., Rosner R., Vaiana G. S., 1979, *ApJ*, 229, 318
- Gaskell, C. M. 1996, in *ASP Conf. Ser. 360, AGN Variability from X-Rays to Radio Waves*, ed. C. M. Gaskell, I. M. McHardy, B. M. Peterson, & S. G. Sergeev (San Francisco, CA: ASP), 111
- Graham A. W., Onken C. A., Athanassoula E., Combes F., 2011, *MNRAS*, 412, 2211
- Gu M., Cao X., 2009, *MNRAS*, 399, 349
- Haardt F., Maraschi L., 1991, *ApJ*, 380, L51
- Haardt F., Maraschi L., 1993, *ApJ*, 413, 507
- Haardt F., Maraschi L., Ghisellini G., 1994, *ApJ*, 432, L95
- Ho L. C., 1999, *ApJ*, 516, 672
- Ho L. C., 2008, *ARA&A*, 46, 475
- Iwasawa, K., Fabian, A. C., Reynolds, C. S., Nandra, K., Otani, C., Inoue, H., Hayashida, K., Brandt, W. N., Dotani, T., Kunieda, H., Matsuoka, M., & Tanaka, Y. 1996, *MNRAS*, 282, 1038
- Kawaguchi T., Shimura T., Mineshige S., 2001, *ApJ*, 546, 966
- Liu B. F., Mineshige S., Ohsuga K., 2003, *ApJ*, 587, 571
- Liu B. F., Yuan W., Meyer F., Meyer-Hofmeister E., Xie G. Z., 1999, *ApJ*, 527, L17
- Loska Z., Czerny B., Szczerba R., 2004, *MNRAS*, 355, 1080
- Lu Y., Yu Q., 1999, *ApJ*, 526, L5
- Malkan M. A., Sargent W. L. W., 1982, *ApJ*, 254, 22
- McHardy I. M., 2013, *MNRAS*, 430, L49
- Merloni A., Fabian A. C., 2001, *MNRAS*, 328, 958
- Merloni A., Fabian A. C., 2002, *MNRAS*, 332, 165
- Meyer-Hofmeister E., Meyer F., 1999, *A&A*, 348, 154
- Mineshige S., Liu B., Meyer F., Meyer-Hofmeister E., 1998, *PASJ*, 50, L5
- Narayan R., 2002, in Gilfanov M., Sunyaev R., Churazov E., eds, *Lighthouses of the Universe: The Most Luminous Celestial Objects and Their Use for Cosmology*. Springer-Verlag, Berlin, p. 405
- Narayan R., Mahadevan R., Quataert E., 1998, in Abramowicz M. A., Björnsson G., Pringle J. E., eds, *Theory of Black Hole Accretion Discs*. Cambridge Univ. Press, Cambridge, p. 148
- Narayan R., Yi I., 1995, *ApJ*, 452, 710
- Qiao E., Liu B. F., 2013, *ApJ*, 764, 2
- Quataert E., Di Matteo T., Narayan R., Ho L. C., 1999, *ApJ*, 525, L89
- Runnoe J. C., Brotherton M. S., Shang Z., 2012, *MNRAS*, 422, 478
- Shakura N. I., Sunyaev R. A., 1973, *A&A*, 24, 337
- Shemmer O., Brandt W. N., Netzer H., Maiolino R., Kaspi S., 2006, *ApJ*, 646, L29
- Shemmer O., Brandt W. N., Netzer H., Maiolino R., Kaspi S., 2008, *ApJ*, 682, 81
- Shields G. A., 1978, *Natur*, 272, 706
- Shu, X. W., Yaqoob, T., Murphy, K. D., Braito, V., Wang, J. X., & Zheng, W. 2010, *ApJ*, 713, 1256
- Sobolewska M. A., Papadakis I. E., 2009, *MNRAS*, 399, 1597
- Suganuma, M. et al. 2006, *ApJ*, 639, 46
- Taam R. E., Liu B. F., Yuan W., Qiao E., 2012, *ApJ*, 759, 65
- Vasudevan R. V., Fabian A. C., 2007, *MNRAS*, 381, 1235
- Wang, J.-X., Wang, T.-G., & Zhou, Y.-Y. 2001, *ApJ*, 549, 891
- Wang, J. X., Zhou, Y. Y., Xu, H. G., & Wang, T. G. 1999, *ApJ* letter, 516, L65
- Wang J.-M., Watarai K.-Y., Mineshige S., 2004, *ApJ*, 607, L107
- Wu Q., Gu M., 2008, *ApJ*, 682, 212
- Xu Y.-D., 2011, *ApJ*, 739, 64
- Xu Y.-D., Cao X.-W., 2009, *RAA*, 9, 401
- Xu Y.-D., Cao X., 2010, *ApJ*, 716, 1423
- Younes G., Porquet D., Sabra B., Reeves J. N., 2011, *A&A*, 530, A149
- Younes G., Porquet D., Sabra B., Reeves J. N., Grosso N., 2012, *A&A*, 539, A104
- Yuan F., Narayan R., 2004, *ApJ*, 612, 724
- Yuan, F., & Narayan, R. 2014, *arXiv*:1401.0586
- Zdziarski A. A., Gierliński M., Mikołajewska J., Wardziński G., Smith D. M., Harmon B. A., Kitamoto S., 2004, *MNRAS*, 351, 791
- Zdziarski A. A., Lubiński P., Smith D. A., 1999, *MNRAS*, 303, L11